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# BOLT BERANEK AND NEWMAN INC

CONSULTING • DEVELOPMENT • RESEARCH

Report No. 2405

FINAL REPORT

STUDY OF THE FEASIBILITY OF
LONG-RANGE SEISMIC COMMUNICATIONS

31 July 1972


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Director, Earth Sciences Division
Earth Physics Program
Office of Naval Research
Department of the Navy
800 N. Quincy
Arlington, Virginia

Attn: Code 417

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## PREFACE

As a task under Contract N00014-72-C-0310 Bolt Beranek and Newman Inc. (BBN) has conducted a 'phase zero' study of the feasibility of achieving hardened communication through the earth over significant ranges using seismic energy. The study was based on an extensive review of the pertinent literature and on discussions with prominent seismologists. This document is the final report of that seismic communication study. Since BBN is not in a position to assess the potential value of such a hardened communication system to the government, it is not appropriate for this report to be interpreted as a recommendation by BBN that a particular course of action be pursued.

## SUMMARY AND CONCLUSIONS

The possibility of using seismic communication systems has often been considered in the past. In order to avoid unnecessary duplication of previous studies this report concentrates on the evaluation of three factors not adequately or explicitly considered in the previous studies we have found. These factors are 1) the state-of-the-art development of controlled sources of seismic energy, 2) use of transmitter and receiver arrays, and 3) recent observations reporting high-Q propagation in $P_n$ mode.

A long range seismic communication system is not practical without the use of a controlled source of seismic energy. Two classes of controlled energy sources are in routine use in seismic exploration, impulsive sources (e.g., the airgun) and controlled waveform sources (e.g., the Vibrose1 ). The primary limitation on both sources is the low output energy level. Although the controlled waveform sources are conceptually more suited to a communication system, the impulsive sources are capable of higher energy output at the present time.

The use of both source and receiver arrays can greatly enhance the capabilities of a seismic communication system. Environmental limitations at the likely source and receiver locations and variations in coupling and near-surface propagation over the area of a large array limit the practical achievable gains. Even with the use of source and receiver arrays, the energy available from present controlled sources falls more than two orders of magnitude below that required for detection of P wave energy over a teleseismic path (2,000 kilometers).

Over distances from about three hundred to two thousand kilometers, the principle short-period propagation mode is $P_n$. The reported attentuation of $P_n$ mode energy varies over an order of magnitude, and quantitative spectral measurements of $P_n$ are very scarce. The expected bit rates and distances for a seismic communication system that can be achieved now are directly dependent on the characteristics of $P_n$ over the chosen path. Judging from the charge sizes used for a few reported long distance measurements of $P_n$ travel times, and assuming rather optimistic gains for arrays and matched filter processing, it may be possible to transmit one bit per minute over distances on the order of 500 kilometers with present technology.

## I. INTRODUCTION AND BACKGROUND

The fact that seismic energy from earthquakes and large explosions can be readily detected by seismic stations all over the world suggests the possibility of using seismic waves for worldwide communications. Although it is clear that seismic communications will be restricted to a narrow bandwidth and will propagate at relatively low velocities, such a system may nevertheless have some unique advantages. This study is undertaken in order to explore the characteristics and potential applications of seismic communications and to determine whether further studies are warranted. The fact that such a communication link would be virtually indestructible (enabling it to serve as a hardened, emergency backup for a limited vocabulary of critical messages) makes an evaluation of the feasibility of seismic communication worthwhile. A brief comparison of the characteristics of possible techniques for achieving a hardened backup communication system will help delineate the potential value of a seismic system.

For communication between two continental sites, use of electromagnetic waves propagating in a deep-crustal highly resistive zone would provide several orders of magnitude more bandwidth and speed than a seismic system would.[1] However, use of a deep-crustal electromagnetic communication link with one terminal in or on the bottom of the ocean may be impractical because of engineering problems resulting from the high conductivity of the ocean water and suboceanic sediment.

Between two oceanic sites acoustic communication through the SOFAR channel would have considerably wider bandwidth than a seismic system, but the propagation times would be greater. For

most cases the engineering problems associated with seismic energy sources would be more severe than those involving SONAR sources. On the other hand, it may not be convenient to locate the receiver in the SOFAR channel. A seismic system thus may be competitive with an acoustic link for communication between distant oceanic terminals.

The fact that seismic waves couple well into underwater acoustic waves suggests that a seismic communication system offers a unique capability for hardened communication from continental to oceanic terminals. These missions, thus, seem to present the best case for use of seismic systems in preference to other forms of hardened emergency communication systems.

Possible use of seismic communications for a variety of applications has been frequently considered in the past and has generally been rejected as impractical, with the exception of certain specialized short-range applications (such as communication from trapped miners with no equipment available except hammers or rocks). The major deterrents to the use of seismic waves for long-range communication have been the narrow bandwidth and low propagation velocity of seismic energy, and the lack of a high-power controlled source.

In the past several years, three new factors have emerged that may influence the practicality of seismic communications. These three factors are 1) development of controlled sources of seismic energy for use in exploration seismology, 2) the use of source and receiver arrays both in exploration seismology and in detection of small earthquakes and explosions at long ranges, and

3) the recognition of high-Q (low attenuation) Phase, $P_n$, near the base of the crust or the upper mantle over wide areas of the world, including the ocean basins.

Under Contract N00014-72-C-0310, Bolt Beranek and Newman Inc. has undertaken a) to review the feasibility of practical hardened communications using seismic means, b) to identify any problem areas, and c) to suggest and estimate costs of an experimental program to resolve the problem areas.

In order to avoid unnecessary duplication of the earlier studies, we have concentrated on examining the three factors listed above to determine whether they have significantly changed the possibility of achieving a practical seismic communication system.

## II. CONTROLLED SOURCES

Long-range seismic communications seem to be impractical without some form of controlled, repeatable source having sufficient output energy. The use of a coded sequence of large explosions as a source for a long-range seismic communication system may be feasible, but it is not practical. Communication over distances of 500 kilometers and beyond would require charge sizes of tens of tons or more.[2] Such shots would be very expensive and could only be used in remote locations where no damage to wells, foundations, etc., could occur. It would be impractical to test the system regularly to insure that it is in operating condition, and the necessity of reloading the holes after each message would demand an interval of several days or weeks between successive transmissions.

In order to avoid the inconvenience of even small explosive sources in exploration seismology, controlled low-energy sources have been developed. The energy output from these sources may conceivably be increased either by combining them in arrays by using larger versions of them. By employing the directivity of a very large source array, the required input energy for a given signal strength in the desired mode and direction may be reduced by as much as the number of elements over that required for a large omnidirectional source such as a single large generator. Use of source and sensor arrays will be discussed in more detail in the next section.

Two classes of controlled seismic energy sources are in use in seismic exploration and research. One group generates impulses similar to explosions. This group includes such devices as airguns and, in marine work, sparkers. The firing rates and energy-per-pulse available for airguns and similar devices are limited by the input energy stored in the form of compressed gas, by the ability of device and medium to dissipate the heat generated, and by the mechanical strength of the gun. Currently the compressors required to generate the input energy seem to present the major problem. Discussions with groups at oil companies and geophysical exploration companies have brought out the fact that 2000-cubic-inch airguns cannot be fired faster than every 10 seconds with present compressor technology. Continuous firing at this rate requires a 500- to 800-horesepower compressor. Smaller airguns can be fired faster, on the order of every 2-3 seconds. An optimal source design for a seismic communication system demands large pulse energy and high pulse rates on the order of 3 firings per second or faster.

Even the 2000-cubic-inch airgun is reported to have an equivalent energy of only 5 pounds of dynamite. Assuming the use of the first arriving compressional phase, P, the detection threshold of a short-period seismometer (assuming about 2.5 milimicrons noise level at 1 hz) at a distance of 2,000 kilometers is equivalent to the signal strength of a magnitude 4 event, corresponding to an explosion of $\sim$1kt ($2 \times 10^6$ pounds) in hard or water-saturated rock (note that the yield/magnitude relation is complex and could easily be in error by an order of magnitude)[3]. Even allowing two orders of magnitude error in interpretation and extrapolation of the source size and yield/magnitude, the required gain of $10^4$ from a single airgun/single seismometer system is not within the limits of current practical array technology. However, an array of deeply buried impulsive sources could provide an energy source for a hardened seismic communication system over shorter distances.

The second class of seismic wave generators are those that produce a controlled waveform such as the Vibroseis. At the lower frequencies (below about 10 hz), the Vibroseis-like systems do not couple energy efficiently into the ground. For a fixed installation, a better controlled waveform source might be a fluid-filled bore hole or cavity driven near resonance by a small hydraulic pump. These devices are generally very narrow band because of inertia of the system, but they would probably improve the coupling efficiency. We have, however, not been able to find quantitative data concerning the performance of such resonant systems. Again, detailed discussions with Vibroseis-oriented groups give us no cause to expect teleseismic (i.e., 2000 km or more) range capabilities from current or next-generation devices,

even with the employment of source and receiver arrays. At the present state-of-the-art, the impulsive sources offer higher potential transmitted energies, and we will assume the use of this type of source throughout the remainder of this report.

Capability estimates are based on an array of 2000-cubic-inch airguns of existing design. If a system were to be implemented, it would probably be possible to design a large gun with an output spectrum better matched to the application, thereby achieving a more efficient system (the peak of the output energy from the high-pressure 2000-cubic-inch guns occurs around 20 hz, which is above likely optimum pass-band of the propagation channel).

## III. SOURCE AND RECEIVER ARRAYS

Both seismometer and seismic source arrays have been routinely used in exploration work for several years. For example, one company employs an array of 30 airguns, each airgun being of 30-cubic-inch-capacity. These systems normally use the energy at frequencies of 20 to several hundred herz, and the routine processing techniques used on the data range from simple beamforming to sophisticated, multidimensional filtering. Large arrays of short-period seismometers operating around 1 hz and long-period instruments with periods of about 20 seconds are being used for teleseismic detection of small earthquakes and explosions. Beamforming has been the routine processing method for these arrays, but extensive experiments using multi-channel and adaptive filtering have been conducted on the data.[4,5]

There are two possible advantages to using an array at the transmitting terminal of the system. First, if there is a practical limit on the power output for a single transmitting element because of power source limitations, heat dissipation, coupling or structural limitations, or potential damage to the environment (buildings, people, etc.), then high-power outputs can be synthesized by using a number of lower-power units. Assuming ideal coupling of all units and coherent combining of the energy from all of the units, the total transmitted power is the sum of that from each of the elements.

The second advantage is that, with appropriate spacing and phasing of the elements in the array, the transmitted energy can be concentrated in a given direction with a given speed to couple optimally into the propagation mode being used. Theoretically, antenna gain may be proportional to the number of sensors, given ideal uniform illumination of the antenna area and ideal coupling.

One of the most serious constraints on the use of a seismic transmitting array is the areal extent of an optimal array. In order to avoid grating lobes in the antenna gain pattern the minimum spacings between elements in the antenna should be about half the wavelength of interest. On the other hand, the total directivity gain of the antenna is determined by the ratio of the antenna diameter to the wavelength. Since the wavelengths of interest for long-range seismic communication are on the order of 0.5 to 10 kilometers, the maximum spacing of the antenna elements should be several tens of kilometers to achieve significant antenna gain. As a result, antennae with high gain are probably impractical in coastal areas where there is usually significant

population buildup, and the use of a large central power source to drive the antenna is likely to be impractical. Another limitation of seismic source arrays is that the geology under the array elements is likely to vary, so that the coupling for the elements is not constant and thus the nonlinear character of the disturbance from each airgun affects every other airgun in a different fashion. A group at Texas Instruments in Dallas with whom we held a discussion has spent the past year on a theoretical study of the design of airgun arrays of modest size, taking into account the non-linear interaction of the airguns. However, they are not sanguine about achieving a large gain from the directivity of such arrays.

We have, therefore, assumed only a gain of the number of elements for a transmitting antenna (i.e., we have assumed that any antenna gain just compensates for loss from non-ideal coupling). We further assume that a maximum size practical for a transmitting antenna is on the order of 10 to 30 elements because of spatial and environmental limitations. For isolated transmitting sites on level ground, it would be possible to achieve a larger antenna with significant antenna gain, but the additional path loss which is paid for the privilege of selecting an ideal site might offset the advantages of the improved antenna.

At the receiver, the main advantage of employing an array is the signal-to-noise gain, and the array limitations and design are primarily controlled by the nature of the noise. The spatial coherence of the noise in the frequency range of the signal is of principal interest in receiver processing and array design. If

the noise is composed of highly organized propagating waves, the array gain may be achieved only if the wave number of the noise is significantly different from that of the signal. The processing required to achieve optimum gain may have to be quite sophisticated and may have to be adaptive if the noise is not stationary. On the other hand, the gain may be well above the square root of the number of sensors under these conditions. If the noise is completely random between elements in the array, simple beamforming is the optimum form of processing and the energy gain approaches the square root of the number of sensors. In practice, only part of the noise is usually coherent and coherence decays with larger sensor separation. As a result there is a tradeoff between the optimum sensor spacing and the optimum processing cost. After extensive experimentation in the Vela large array program it was found that for the short-period range (0.8 to 3 hz) at continental sites the optimum design required spacing of the sensors about 3 kilometers apart to make the noise appear incoherent, and the use of simple beamforming for array processing.[6] During our discussions with Prof. Sutton and his staff at the Hawaii Institute of Geophysics, they indicated that the noise on the sea floor at the same frequencies may be much more coherent. On the other hand, at higher frequencies the seismic noise tends to be less coherent.

Adequate tuning of the complex processing necessary to achieve optimum array gain against highly coherent noise would be difficult in an inaccessible environment such as the sea floor, so the system design should minimize the complexity of the receiver processing. As with the transmitting array, the area required

for a large receiving array that can be highly selective in wave number may not be available at the receiving terminal. As a compromise we assume a reasonable receiver array gain of about one order of magnitude (corresponding to $\sqrt{N}$ gain for a 100-seismometer array) in a seismic communication system. Thus, assuming the short-period (1 to 10 hz) propagation, the expected gain for a seismic communication system using transmitting and receiving arrays is on the order of 100 in amplitude.

## IV. $P_n$ PHASE

Over distances of 300 to 2 or 3 thousand kilometers, the propagation phase commonly called $P_n$ is usually the most prominent short-period phase. Recent observations suggest that $P_n$ may have lower attenuation and higher bandwidth than the mantle P phase (and therefore be more promising in terms of seismic communication).[7,8]

Studies made to confirm and better define the new theories of plate tectonics suggest that $S_n$ and $P_n$ propagate well within any given plate, but that they do not propagate across subduction zones or spreading zones at plate boundaries. There is some evidence, however, that $P_n$ and $S_n$ do cross the transform faults associated with spreading regions, suggesting that they may be able to cross some sections of plate boundaries.[7] Recent studies of the lower crust and upper mantle of the Pacific Ocean basin indicate that $P_n$ may be particularly consistent over large areas under the deep oceans.[9]

The actual propagation mechanism for $P_n$ has not been determined. The propagation path seems to be below the moho but above

the low-velocity region of the upper mantle. The phase has been called a head wave, a leaky mode, or a channeled or guided wave. For our purpose, the actual propagation mode is not so important as the attenuation and bandwidth characteristics and the continuity of the propagation. Speculation about the value of Q for $P_n$ propagation over the stable part of crustal plates and the ocean floor varies from under 1000 to around 5000. We have, however, been unable to find a set of reliable, consistent measurements of Q for $P_n$. Extensive data taken from the Cannikin shot in the Aleutians is available, and attempts to estimate Q for the North Pacific basin may provide the first reliable measurements of Q for $P_n$.

Observations of strong higher frequency (3 to 10 hz) energy in $P_n$ mode are reported from several sources.[1,7,9] Many of these observations have been based on data from hydrophones that cut off at the lower frequencies, so the data cannot be directly compared with conventional short-period seismometer data on the mantle P phase. Even accounting for the instrument response and a high value for Q, the spectral content of $P_n$ seems to be rich in high-frequency energy, indicating that $P_n$ cannot be considered as a high-Q version of P. Frantti made measurements on $P_n$ propagation over a 350 km path off the coast of Maine and found the Q for $P_n$ to be frequency-dependent. His data gave Q at 2 hz of 104, Q at 5 hz of 252, and Q at 10 hz of 510.[10] Thus the low-frequency cutoff of $P_n$ appears to be a propagation phenomenon (perhaps involving propagation in a waveguide-like channel near or below cutoff). Again, we have been unable to find any reliable quantitative spectral measurements of $P_n$ and P over comparable paths from the same source. These measurements could be readily made from the digitized data from the Cannikin explosion.

Another frequently-reported characteristic of $P_n$ is a long complex wave sequence that dies off much more slowly than the more impulsive P. $P_n$ energy spread over 30 to 45 seconds is not unusual. As was pointed out in the Texas Instruments report on seismic communication, a matched filter designed to compress this wave train can achieve an energy gain proportional to the time bandwidth product of the signal.[11] Assuming a 30-second signal with a bandwidth from 3 to 10 hz (7 hz), matched filtering could gain as much as a factor of 10 in amplitude. By combining source and receiver array gains with matched filter gains, one might achieve a maximum possible three-order-of-magnitude gain in amplitude over the single pulse peak amplitude of the $P_n$ phase.

A property of $P_n$ propagation of particular interest for a continental-to-oceanic communication path is its behavior at the continental boundary. Since $P_n$ propagates in the lower crust or upper mantle, it is likely to be strongly affected by the change in crustal thickness at the boundary between the ocean basin and a continent or even an island. The only data we have found that bear on this question are comparisons of data from the ocean bottom seismometer off the coast of California with data taken from the interior of California. Interpretation of these data is complicated by the fact that the measurements can be explained by the influence of the low-velocity region below the western mountain ranges which extends almost to the continent/ocean boundary along that coast.[12] $P_n$ from the Cannikin explosion has been recorded in the Pacific Ocean, and quantitative analysis of that data would aid in defining the effect of this boundary.

Thus, although $P_n$ potentially has a significant influence on the practicality of seismic communications, there is very little quantitative data on $P_n$ propagation to be used in assessing this influence.

Working in the relatively noisy seismic environment of the New England coast, Frantti reported signal pulse detection of shots of one ton fired on the ocean bottom under 300 meters of water over paths of 350 kilometers. Assuming an amplitude gain of 1000 over a single 2000-cubic-inch airgun, this suggests that $P_n$ from a 10- to 30-element array of 2000-cubic-inch airguns could be detected at distances on the order of 500 km from the source. Alexander and Greenfield quote several additional surveys which are essentially in agreement with these values in the intermediate ranges where $P_n$ would be the primary arrival; however, they do not distinguish which arrival was actually measured.[2]

## V. CONCLUSIONS AND POSSIBLE FUTURE EFFORT

In order to be practical for any mission, a seismic communication system must be based on a controlled and repeatable source of energy. Although impulsive sources such as airguns are not optimum signal sources for communication, in terms of the amount of energy that can be transmitted, impulsive sources appear to be significantly superior to controlled waveform sources at the present state-of-the-art. We therefore consider that impulsive sources are the best available energy sources for a seismic communication system.

Using the present state-of-the-art and being somewhat optimistic about performance from transmitter and receiver arrays

and from sophisticated receiver processing, it may be possible to communicate over distances on the order of 500 km by seismic means in an area of strong, consistent $P_n$ propagation. In order to achieve an adequate detection probability for reliable communication and to spread the energy for each symbol over sufficient time that it is not likely to be masked by energy from an earthquake or other transient event, each symbol would have to be represented by approximately ten or more individual pulses of the source. A possible symbol coding, for example, might represent each symbol by a different pulse rate for a sequence of 10 pulses, starting with one pulse every ten seconds for the highest rate symbol and reducing the pulse separation by a half-second between symbol values. The implied data rate is on the order of 1 bit/minute, and the travel time from transmitter to receiver for a 500-km link is about 60 seconds.

In order to achieve this performance we assume a three-order-of-magnitude gain in amplitude from the combination of a 10- to 30-element transmitting array of 2000-cubic-inch airguns, and a 100-element receiving array with matched filtering. This assumption particularly implies rather sophisticated receiver processing since there would be considerable energy overlap between successive pulses in a symbol and between symbols themselves. Other propagation modes such as P, $P_g$, and surface waves may also introduce interfering energy that may place constraints on the optimum receiver array geometry.

The capabilities assumed for the state-of-the-art system described above are strongly dependent on the propagation characteristics of $P_n$, which are known at best only to an order

of magnitude and may vary widely for different paths. Since it appears that $P_n$ will be the critical mode for long-range seismic communication up to ranges of 2000 or 3000 kilometers, it is evident that the next step in better determining the feasibility and capability of seismic communications is to learn more about propagation of $P_n$ over paths typical of those that may be interesting for potential applications. A likely application would be communication from a coastal site to the deep ocean, and data for such a path are already available from the Cannikin nuclear explosion, as are good data from continental paths. The oceanic data are being analyzed at the Hawaii Institute of Geophysics for travel times, and an attempt will probably be made to measure Q for the $P_n$ phase on a path running from the Aleutians toward Hawaii. However, since the Q for $P_n$ appears to be strongly frequency-dependent over frequencies from 1 to 10 hz, a simple Q measurement is likely to be relatively meaningless.

We have tried, at the beginning of this section, to summarize the capability we consider possible with the state-of-the-art technology. We believe the estimate of the capability is good to within a factor of 2 or 3 in range and a factor of 4 in data rate, and that actual capability will vary over that range from site to site.

If the projected capability described above is even marginally interesting, and if the government decides that a further investment of funds is justified, then we suggest that further analysis of the Cannikin data should be completed before any more expensive experiments explicitly designed to investigate a communication system are undertaken. Specifically,

digital data from a continental and an oceanic path, each 2 to 4 thousand kilometers long, should be used to determine the time and frequency distribution of energy in the oceanic and continental $P_n$ and P phases. The results of the analysis would provide a basis for 1) a better estimate of system capability, 2) an optimum design for a communication experiment, and 3) an assessment of the effect of the ocean boundary. Since most of the data appear to be already in hand, the cost of data collection and the necessary digital analysis would be relatively small, perhaps on the order of 25 to 35 thousand dollars. Data for the oceanic path are available at the Hawaii Institute of Geophysics, and the staff at the Institute understand the complex calibration procedures involved in using the sonobuoy data. That institute thus seems like a good candidate to complete the analysis. Data for a continental path running from Alaska roughly down the eastern side of the Rocky Mountains, including data from the Yellowknife and LASA arrays, should be available through Vela Seismologic centers in Alexandria and could be augmented from selected WWSS data (digitization of the latter data may present a problem).

If the results of this analysis are encouraging and the projected capability for a communication system were of interest for a particular mission, then the next step would be to perform an experiment using a controlled source array and a receiver array to confirm the predicted signal-to-noise gains. The receiver processing for the first experiment would, of course, be performed off-line from recorded data to save the cost of an expensive on-site receiver processing system, and to allow flexibility in experimentation with the form of the receiver processing. The experiment could essentially be performed with

currently available source and receiver equipment and would likely cost about $250K to $400K, depending on equipment availability. The source array could consist of 5 to 10 airguns in the 100- to 200-cubic-inch range. The receiving terminals might comprise three arrays of 10 to 30 (depending on distance from the source) sonobuoys with electronics modified for the appropriate frequency range. Data from at least one ocean-bottom seismometer far enough from the source to observe $P_n$ would be a valuable aid in interpreting the results of the experiment.

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